*Agricultural and Forest Meteorology*, 46 (1989) 15-22
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands


# AERODYNAMIC PROPERTIES OF PARTIAL CANOPIES*

J. L. HATFIELD
*USDA-ARS, Rt. 3, Box 215, Lubbock, TX 79401 (U.S.A.)*
(Received November 3, 1987; revision accepted September 20, 1988)

## ABSTRACT

Hatfield, J.L., 1989. Aerodynamic properties of partial canopies. Agric. For. Meteorol., 46: 15-22.

Roughness lengths ($z_0$) and displacement heights ($d$) are often assumed to be simple functions of canopy height. This study was designed to evaluate these canopy aerodynamic properties for cotton (*Gossypium hirsutum* L.) having partial ground cover. Both $z_0$ and $d$ were calculated from wind profile measurements for neutral conditions as defined with a Richardson number over irrigated and rainfed cotton in 1984 and 1985. Throughout the season $z_0$ started at 0.01 m and increased to a maximum of 0.20 m then declined to a value of 0.06 m when the canopy reached 70% ground cover. This change throughout the season was caused by the individual rows first acting as discrete bluff-bodies and then as a more uniform surface as the foliage elements overlapped as the canopy developed. Displacement heights increased linearly throughout the season as the canopy increased in height and leaf area.

## INTRODUCTION

The rate of mixing above and within canopies is dependent upon the roughness lengths and displacement heights in the calculation of aerodynamic resistance. The electrical analog approach to describing how canopies are coupled with the atmosphere has promoted the use of aerodynamic resistance nomenclature. Estimates of $z_0$ and $d$ are often assumed to be simple relationships with height as shown by Stanhill (1969), Szeicz et al. (1969), Begg and Monteith (1975) and Brutsaert (1975). However, these relationships were developed for the full canopy conditions with complete ground cover. Stanhill (1969) proposed that $z_0 = 0.13H$ where $H$ is the crop height (m) and that $d = 0.65H$. These coefficients are often assumed to hold for all ranges of canopy development.

Verma and Barfield (1979) cited unpublished data from John Norman which showed that $z_0$ changed as a function of the height/width ratio for row crops. Lettau (1969) had earlier proposed that, for discrete objects, a ratio of the

*Contribution from USDA-ARS.

silhouette area to the total area of an object would provide a good description of $z_0$ for partial canopies. Hatfield et al. (1985) found, for partial canopies of cotton, that $z_0$ values were approximately $0.25H$ rather than the often assumed $0.13H$. This difference in roughness length caused a more rapid exchange of sensible heat between the crop and the atmosphere.

De Bruin and Moore (1985) showed that $z_0$ and $d$ could be easily estimated for tall vegetation using a mass conservation method. This result was an extension of earlier work by Molion and Moore (1983). Their approach may be easier to apply than wind profile measurements, however sonic anemometers are required to obtain the vertical fluxes.

Finnigan (1985) has proposed that electrical analogs of the flux-gradient models of turbulent transport are not applicable or accurate. However, for bulk exchange processes the flux-gradient method still may be applicable, particularly where many models such as the Penman–Monteith evaporation model or the surface energy balance model (Hatfield et al., 1984) are used to estimate the total evaporation flux.

Roughness lengths and displacement heights for partial canopies are needed to more accurately quantify the flux-gradient method. The objective of this study was to evaluate $z_0$ and $d$ for partial cover row crops throughout the growing season and to relate canopy aerodynamic properties to canopy growth parameters.

## MATERIALS AND METHODS

### *Experimental procedures*

Cotton (*Gossypium hirsutum* L.) var. Paymaster 145, a broad-leafed variety, was planted on 29 May 1984. On 29 May 1985 two varieties, Paymaster 404, a broad-leafed variety and Gumbo, a supraokra leaf shape, were planted. These varieties were chosen to allow for a range of leaf area while maintaining similar crop heights throughout the season. The seedbed was prepared in 1 m N–S rows with the furrow height at planting of approximately 0.1 m. Prior to planting a herbicide, Prowl, was applied and incorporated and nitrogen fertilizer as anhydrous ammonia was incorporated at the rate of 70 kg ha$^{-1}$. A preplant irrigation of 100 mm was applied approximately 20 days before planting to insure emergence. After planting, the plot area was divided into two soil water treatments, irrigated and rainfed. The irrigated plot received two irrigations of 110 mm each throughout the season. During the growing season precipitation totals for 1984 and 1985 were 219 and 369 mm, respectively. Each soil water treatment was $50 \times 100$ m in size with a north–south row orientation. Surrounding the plot area was cotton of the same variety and similar soil water management practices to allow an effective fetch to the south and south-west directions in excess of 300 m.

A micrometeorological tower containing four aspirated psychrometers and anemometers was located within each plot. The psychrometers used were platinum resistance probe thermometers and had a ventilation rate in excess of 3 m $s^{-1}$. The wet bulb thermometer was covered with a 6 mm o.d. ceramic wick that was fed water from a constant head device. Windspeed was measured with R.M. Young d.c. generator anemometers* which were calibrated with voltage standards before and after each growing season. The accuracy of the psychrometers was $\pm 0.05$°C and the anemometers was $\pm 0.1$ m $s^{-1}$. Daily checks were made to insure instrument stability. These instruments were positioned at 0.10 m below the canopy top midway between the rows, and at 0.25, 0.5 and 1.0 m above the canopy and moved weekly to maintain these heights. Previous data collected by Hatfield et al. (1985) with five levels of windspeed up to 2 m above the canopy revealed that $z_0$ and $d$ could be estimated from towers to a height of 1 m. This protocol was followed for the subsequent studies. The towers were positioned near the north-east corner of the plot to provide maximum fetch because of the prevailing south–south-west winds. Wind direction was measured with an R.M. Young 360° wind vane* positioned at 2.5 m above the soil surface.

All instruments were sampled at 1-min intervals with a 15-min average computed and stored on disk. The data were transferred to a larger computer for analysis at the end of the season. The measurements commenced shortly after emergence and continued until late September.

Plant measurement were made weekly in all treatments on 10 randomly-selected plants. Measurements made included leaf area, plant height, phenological stage, number of green leaves and dry biomass. These measurements commenced at emergence and continued until frost stopped the growth of the plant.

### *Data analysis*

On each day throughout the season the data were screened to eliminate obvious problems and to exclude data in which the wind direction was not between 160° (SSE) and 235° (SW) from north. The remaining data were analyzed with an interactive computer program to obtain $z_0$ and $d$ for neutral conditions. For each 15-min time interval neutrality was determined by a calculation of the Richardson number based on the temperature and windspeed differences from the 0.25 and 1.0 m height. The limits chosen for acceptance of the data were between a Richardson number of $-0.1$ to $+0.1$. These conditions often occurred during the night time and early morning hours.

---

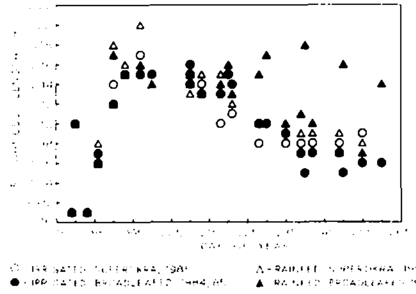
*Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the United States Department of Agriculture, and does not imply its approval to the exclusion of other products that may also be suitable.

Roughness lengths and displacement heights were obtained in the method shown by Monteith (1973) and Robinson (1962). This procedure involved setting a value of $d$ and then computing the slope of the resulting line which was tested for linearity. A new value for $d$ was then assumed and the improvement in the fit evaluated. This procedure was followed until no improvement in $z_0$ was obtained. The procedure allowed for rapid analysis using a least squares procedure. Using this procedure 1 day's data could be analyzed in less than 5 min.

## RESULTS AND DISCUSSION

### *Roughness lengths and displacement heights*

Roughness lengths varied throughout the season as shown in Fig. 1, while displacement heights exhibited a linear increase throughout the season (Fig. 2). The variabilities in both $z_0$ and $d$ are due to the soil water treatment and the amount of canopy growth. Even though the wind direction varied from parallel to near-perpendicular to the rows there was no significant effect on the values for $z_0$ and $d$ on a given day (data not shown). This is possibly due to the lack of consistency in the wind direction over a 15-min period for this area and the partial canopy conditions. On each day all of the available $z_0$ and $d$ data were averaged to obtain a value for the day, thus the number of points varied on a given day. The minimum number of data points used for each day was five 15-min intervals. The coefficient of variation about the mean for both $z_0$ and $d$ was less than 10%. Values of $z_0$ exhibited large differences toward the end of the season because there were differences in growth between the years due to the available soil water (Fig. 1). The values of $d$ also exhibited differences between years, particularly as the season progressed (Fig. 2). Thus, both of these aerodynamic parameters are not simple functions of time during the season.



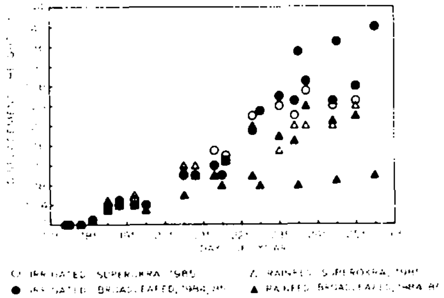


Fig. 1. Patterns of roughness lengths, $z_0$, as a function of day of year for cotton in 1984 and 1985.

Fig. 2. Patterns of displacement height, $d$, as a function of day of year for cotton in 1984 and 1985.

The growth differences between canopy types and soil water treatment did not affect the roughness lengths or displacement heights. Leaf area differences between the supraokra and broad-leafed canopies were 30% throughout the season, however the heights of the two canopies were the same. The 1984 rainfed broad-leafed plants were smaller in leaf area and height later in the season and this is reflected in the effect on $z_0$ and $d$ (Figs. 1 and 2, respectively). Following the approach suggested by Verma and Barfield (1979) height/width ratios ($H/W$) were calculated based on the height of canopy and the distance between rows. Thus, in this study the $H/W$ ratio is the same as canopy height since the row spacing was 1 m. However, for subsequent analyses these parameters often vary and the framework to compare data sets exists.

Variation of $z_0$ with height/width ($H/W$) exhibited a rapid increase as the plants developed and then decreased as the canopy height increased above 0.25 m (Fig. 3). At the beginning of the season $z_0$ values were approximately 0.01 m. As growth continued when the canopy reached a height of 0.25 m the roughness lengths attained a maximum of 0.2 m. At this growth stage the cotton canopy consists of primarily mainstem leaves with no branches, thus the canopy is characterized by well-defined rows with no interactions between the foliage elements from adjacent rows. The canopy remained aerodynamically rough with $z_0$ values greater than 0.15 m until the $H/W$ ratio exceeded 0.45 (Fig. 3). At this time the stems had begun to produce branches and the rows began to interact with each other. From that time on the roughness lengths continuously declined to a value of 0.06 m (Fig. 3). This pattern of $z_0$ with $H/W$ ratio was prevalent for both soil water treatments and canopy types. It was not possible to separate the canopy types although the leaf areas differed by 30%. The relationship between $z_0$ and $H/W$ is shown in Fig. 3.

The data presented in Fig. 3 represent two populations with a quadratic relationship up until an $H/W$ ratio of 0.5 and then a linear decrease as the $H/W$ increased above 0.5. This relationship is similar to that shown by Verma and Barfield (1979) with a rapid change in $z_0$ at values of $H/W$ less than 1.

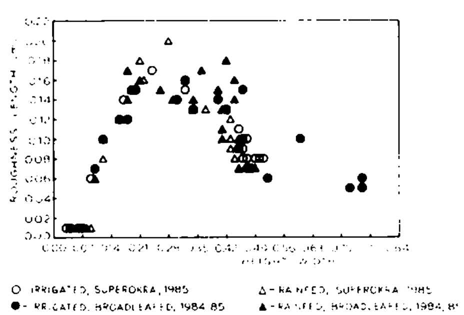


Fig. 3. Variation of roughness length as a function of canopy height/row width ratio for cotton in 1984 and 1985.

TABLE 1

Coefficients for linear regressions of $z_o$ and $d$ vs. $H/W$ ratios for different leaf shapes and irrigation treatments in cotton

| Leaf type | Irrigation | Intercept | $H/W$ | $(H/W)^2$ | $r^2$ |
|---|---|---|---|---|---|
| *Roughness length* | | | | | |
| Broadleaf | Dryland | −0.0474 | 1.4689 | −2.504 | 0.96 |
| Broadleaf | Irrigated | −0.0942 | 1.9389 | −3.424 | 0.87 |
| Supraokra | Dryland | −0.0533 | 1.4829 | −2.567 | 0.91 |
| Supraokra | Irrigated | −0.0667 | 1.5611 | −2.613 | 0.70 |
| Combined data | | −0.0634 | 1.5851 | −2.725 | 0.83 |
| *Displacement height* | | | | | |
| Broadleaf | Dryland | −0.0168 | 0.3273 | | 0.97 |
| Broadleaf | Irrigated | −0.0492 | 0.4976 | | 0.83 |
| Supraokra | Dryland | −0.0457 | 0.4874 | | 0.83 |
| Supraokra | Irrigated | −0.0410 | 0.4294 | | 0.72 |
| Combined data | | −0.0397 | 0.4447 | | 0.80 |

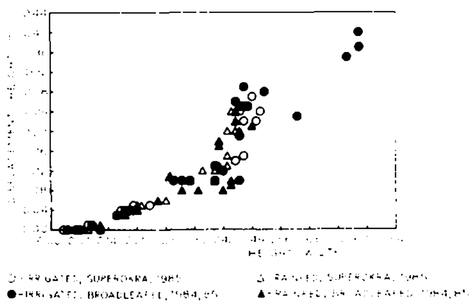


Fig. 4. Variation of displacement height as a function of canopy height/row width ratio for cotton in 1984 and 1985.

The individual regression equations for each soil water or canopy-type treatment were not different in their form or goodness of fit (Table 1). These equations represented the best form of the relationship between $z_o$ and $d$ vs. $H/W$ and addition of terms did not improve the fit. These results are applicable to the early growth of a row crop and suggest that a more narrow row spacing, hence a more rapid increase in the $H/W$ ratio, would be advantageous because the smoother aerodynamic canopy would have a greater aerodynamic resistance as shown by J.L. Hatfield (1987, unpublished data).

Displacement height increased linearly as the $H/W$ ratio increased (Fig. 4). As the canopy height increased the adjustment necessary in the height in order to satisfy the conditions of the log-wind profile under neutrality increased. This result is to be expected since the taller the canopy the more displacement in the $z_0$ length is necessary. Displacement height was significantly correlated with leaf area index and canopy height ($r = 0.78$ and 0.89, respectively). These data show that displacement height is simply related to canopy height while $z_0$ is a more complex function of canopy growth.

The values of $z_0$ obtained in this study are much larger than would be expected given the height of the canopy. There are two possible explanations for the fact that $z_0/H$ often exceeds 0.5. First, the errors in the profile measurement mask the true values and second, the structure of the canopy configuration violates the assumptions of the log-law profile. The consistency of the $z_0$ and $d$ parameters suggests that the measurements and analysis are sufficient. The assumption of a log-law profile is based on a uniform surface which partial canopies do not fit. Cotton canopies grown in these studies are quite dense with a high foliage density within the volume occupied by the leaves. These results suggest that additional studies be undertaken in this area to more fully understand the coupling of plants and the atmosphere in dryland agriculture.

Partial canopies with incomplete ground cover are aerodynamically rough with rapid increases in $z_0$ early in the season. However, as the canopy begins to branch and the individual rows interact the $z_0$ values become linear functions of height. These parameterizations of $z_0$ and $d$ will be useful in quantifying energy exchanges in dryland areas with small canopies throughout the season and improve our understanding of plant–atmosphere interaction.

## REFERENCES


Begg, B. and Monteith, J., 1975. Heat and mass transfer within plant canopies. In: D.A. de Vries and N. H. Afgan (Editors), Heat and Mass Transfer in the Biosphere. I. Transfer Process in Plant Environment. Wiley, New York, pp. 167-186.

Brutsaert, W., 1975. Comments on surface roughness parameters and the height of dense vegetation. J. Meteorol. Soc. Jpn., 53: 96-97.

De Bruin, H.A.R. and Moore, C.J., 1985. Zero-plane displacement and roughness length for tall vegetation, derived from a simple mass conservation hypothesis. Boundary-Layer Meteorol., 31: 39-49.

Finnigan, J.J., 1985. Turbulent transport in flexible plant canopies. In: B.A. Hutchison and B.B. Hicks (Editors), The Forest-Atmosphere Interaction. Reidel, Dordrecht, pp. 443-480

Hatfield, J.L., Reginato, R.J. and Idso, S.B., 1984. Evaluation of canopy temperature evapotranspiration models over various crops. Agric. Meteorol., 32: 41-53.

Hatfield, J.L., Wanjura, D.F. and Barker, G.L., 1985. Canopy temperature response to water stress under partial canopy. Trans. ASAE, 28: 1607-1611.

Lettau, H.H., 1969. Note on the aerodynamic roughness - Parameter estimation as the basis of roughness - Element description. J. Appl. Meteorol., 8: 828-832.

Molion, L.C.B. and Moore, C.J., 1983. Estimating the zero-plane displacement for tall vegetation using a mass conservation method. Boundary-Layer Meteorol., 26: 115-125.

Monteith, J.L., 1973. Principles of Environmental Physics. Arnold, London, pp. 241.

Robinson, S.M., 1962. Computing wind profile parameters. J. Atmos. Sci., 19: 189-190.

Stanhill, G., 1967. A simple instrument for the field measurement of turbulent diffusion flux. J. Appl. Meteorol., 8: 509-513.

Szeicz, G., Endrodi, G., and Tachman, S., 1969. Aerodynamic and surface factors in evaporation. Water Resour. Res., 5: 380-394.

Verma, S.B. and Barfield, B.J., 1979. Aerial and crop resistances affecting energy transport. In: B.J. Barfield and J.F. Gerber (Editors), Modification of the Aerial Environment of Crops. Am. Soc. Agric. Eng., St. Joseph, MI, pp. 230-248.